PHENIX Summer 2010 Collaboration Meeting, July 12

QCD: the next decade

D. Kharzeev

BROOKHAVEN NATIONAL LABORATORY

Outline

- The beginnings

  From atoms (V century B.C.) to quarks;
  atoms, void and geometry
- The successes

  Symmetry; QCD as the gauge theory of strong interactions;
  asymptotic freedom; hard processes; strong color fields
- The challenges

  Confinement; chiral symmetry breaking; extreme QCD:
  temperature, density, energy; the spin; void and geometry
- The mission for the next decade

  From particles to fields: collective phenomena
  as the essence of QCD; the measurements

The beginnings

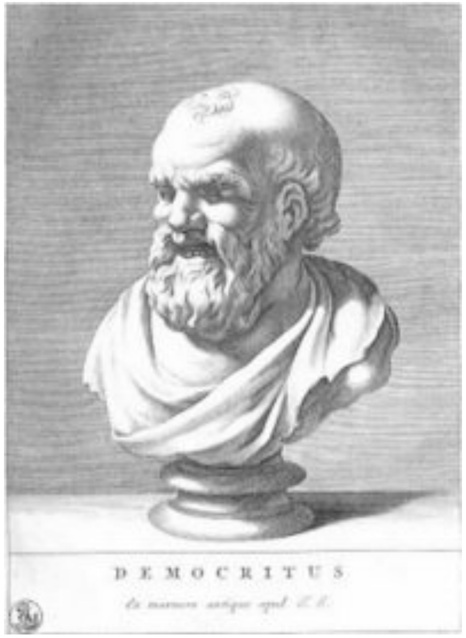
Everything consists of

<u>Atoms and Void</u>

Λεύκιππος
Leucippus, V B.C.

ἄτομος   un - cuttable, indivisible

α-   τέμνω

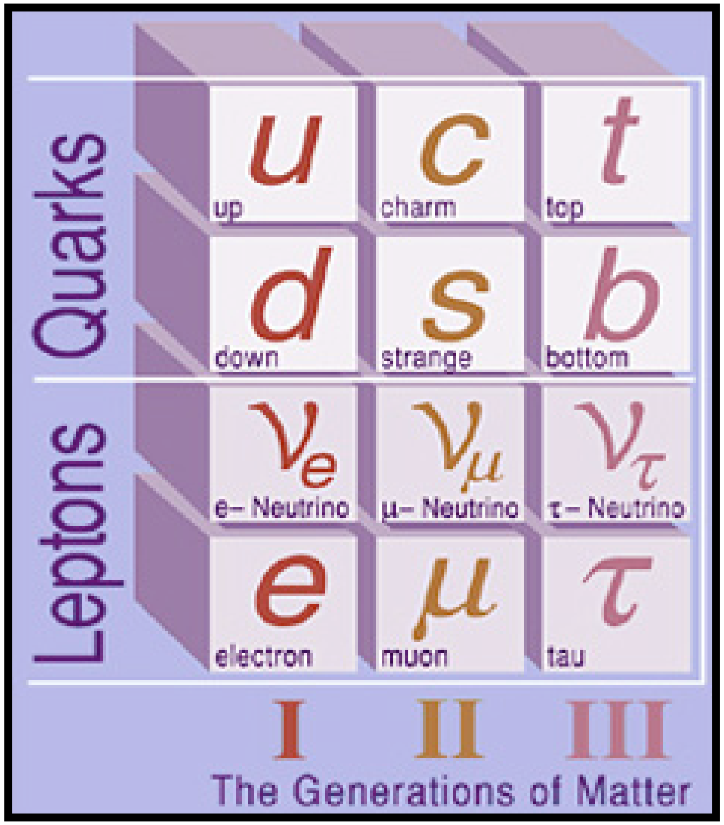


Δημόκριτος
Democritus, ca 460 -370 B.C.

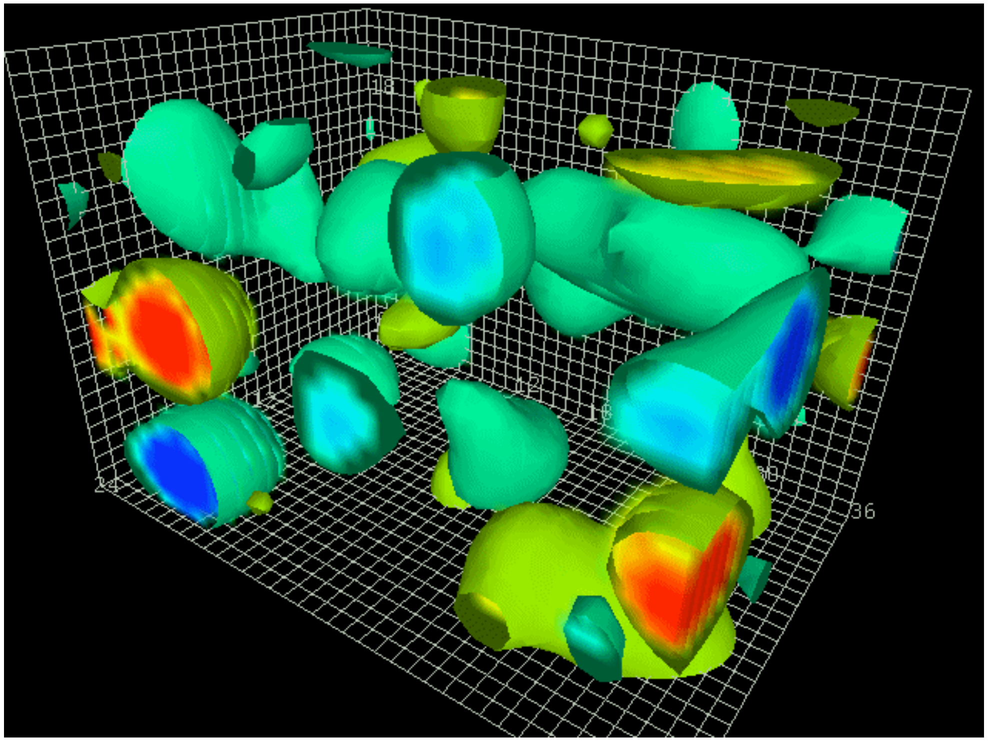
Everything consists of

Atoms and Void

"Atoms",
ca 2010 A.D.



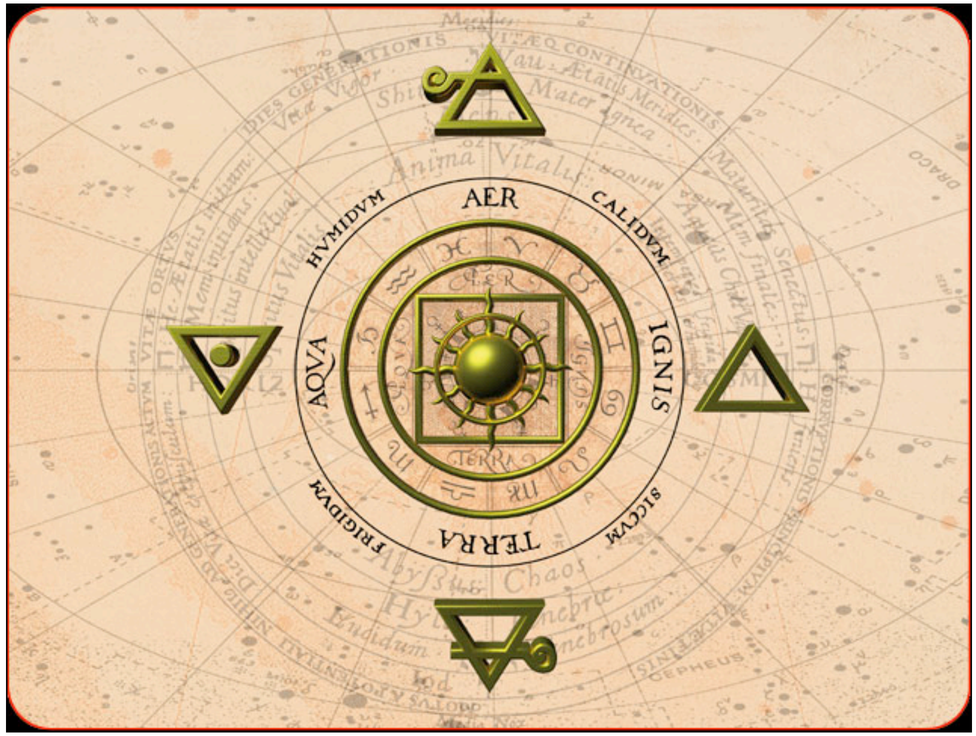
Void,
ca 2010 A.D.



Atoms and Geometry, IV B.C.

Πλάτων

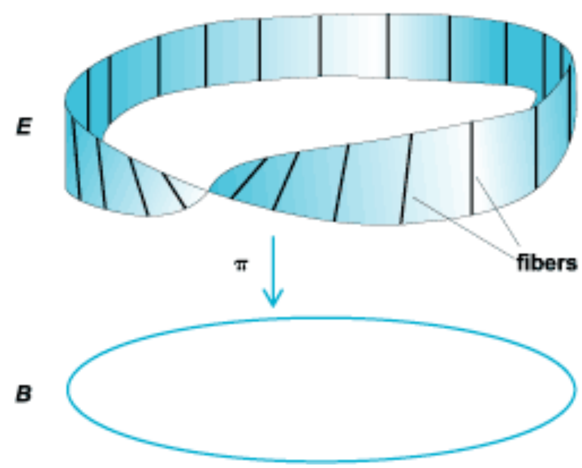
Plato, 428-348 B.C.



Fire **Air** **Water** **Earth**

Atoms and Geometry, 2010 A.D.

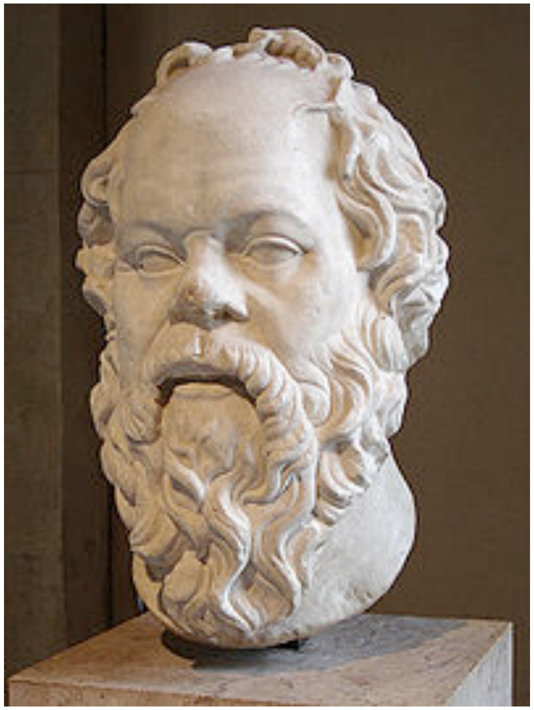
Geometry	⟷	**Physics**
Riemannian connection	⟷	Gauge field
Curvature tensor	⟷	Field strength tensor



Möbius strip, the simplest nontrivial example of a fiber bundle

Gauge theories "live" in a fiber bundle space that possesses non-trivial topology (knots, links, twists,...)

The metaphor of the cave, 380 B.C.



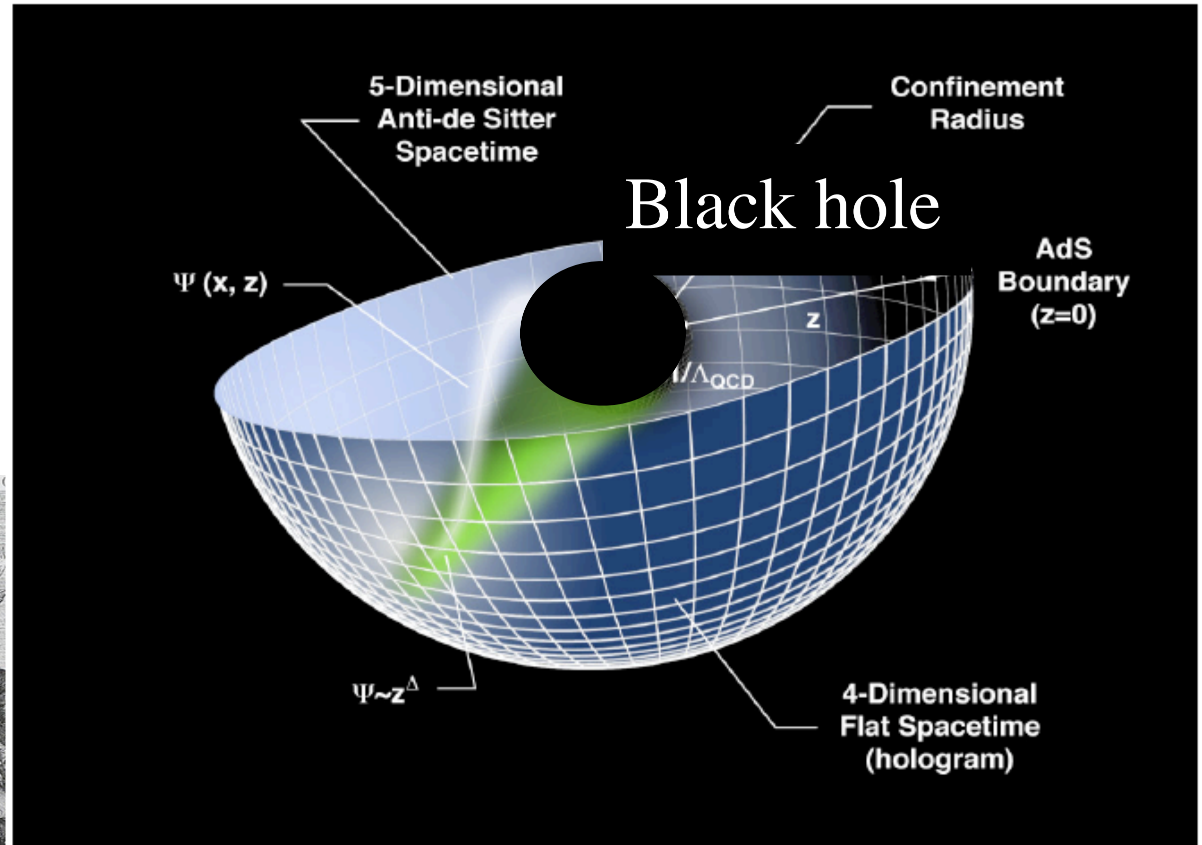
Socrates (Σωκράτης)
469 - 399 B.C.

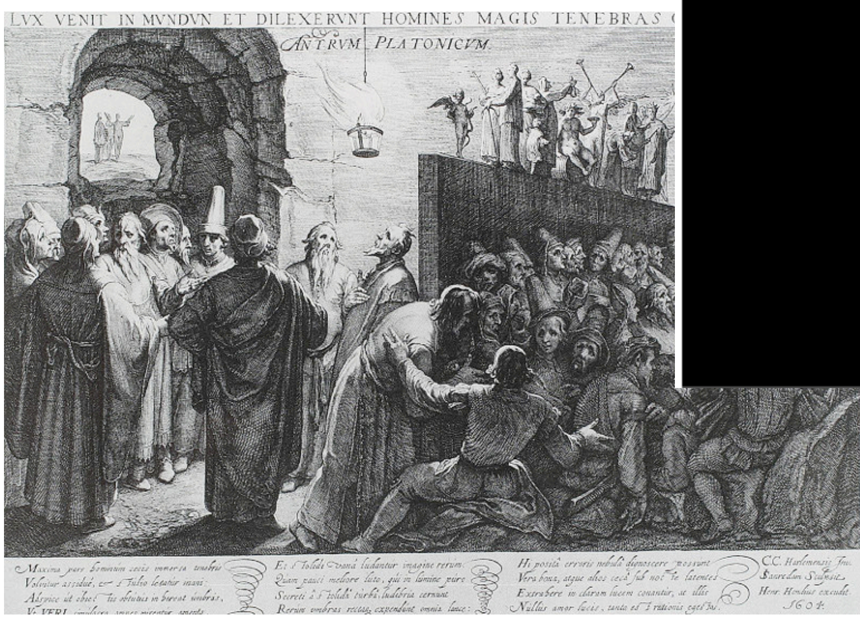
“Physical objects and physical events are only "shadows" of their ideal or perfect forms, and exist only to the extent that they instantiate the perfect versions of themselves”

Socrates, in Plato’s “Republic”

“The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard.”

The metaphor of the cave, 2010 A.D.





“The prisoners would take the shadows to be real things and the echoes to be real sounds, not just reflections of reality, since they are all they had ever seen or heard.”

The successes

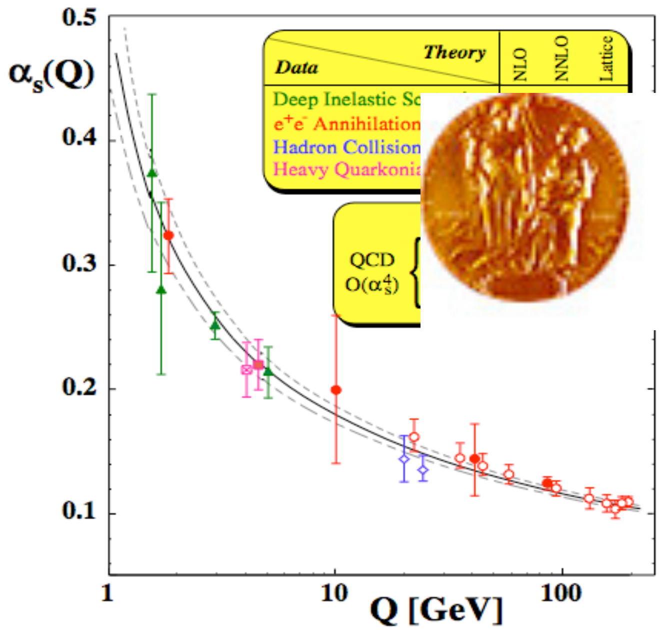
QCD = quarks + geometry

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_f \bar{q}^a_f (i\gamma_\mu D_\mu - m_f) q^a_f;$$

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

Elegant, consistent, and correct theory

Asymptotic Freedom: "atoms" revealed



At short distances,
the strong force becomes weak
(anti-screening) -
one can access the "asymptotically free" regime in hard processes

and in super-dense matter
(inter-particle distances ~ 1/T)

$$\alpha_s(Q) \simeq \frac{4\pi}{b\ln(Q^2/\Lambda^2)}$$

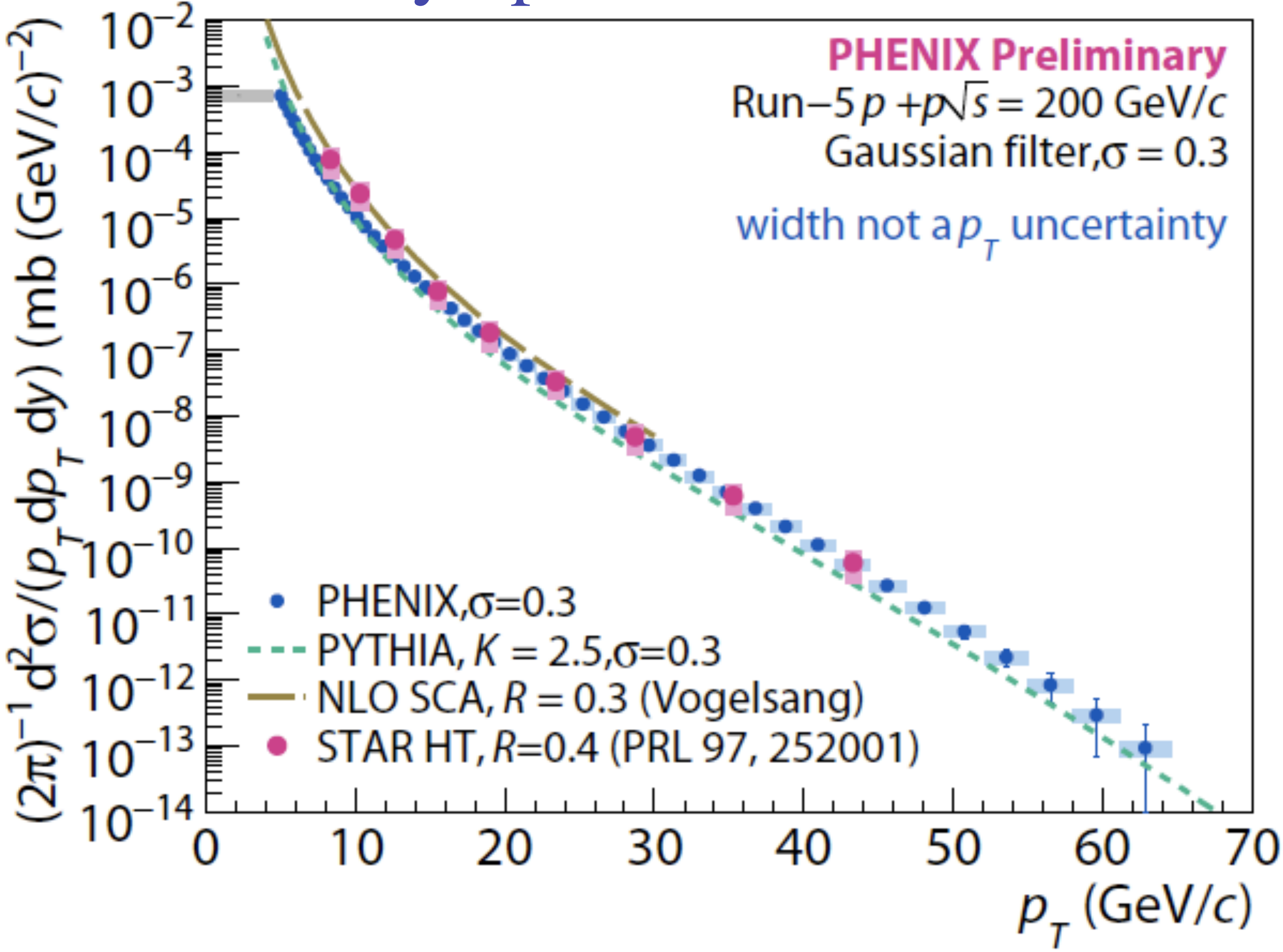
number of colors

number of flavors

$$b = (11N_c - 2N_f)/3$$

But: Strong confining interaction at large distances

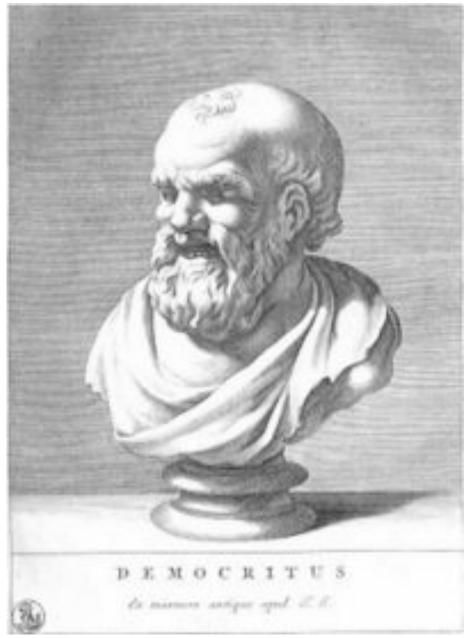
Asymptotic Freedom



Y.Lai, PHENIX Coll, June 2010

Where do we stand? (V B.C.)

- "Atoms"
- Geometry
- Void



Where do we stand?
(2010 A.D.)

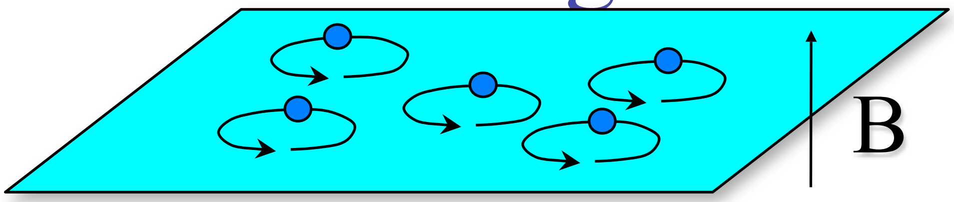
- [x] "Atoms" identified: quarks and leptons
- [ ] Geometry (gauge field dynamics)
- [ ] Void (the structure of the vacuum)

The next step:
from particles ("atoms") to fields (geometry)

QCD: understanding the dynamics of gauge fields (geometry)

Problem		Measurements at RHIC
Weak/vacuum fields	$\leftrightarrow$	Spin, parton fragmentation
Strong static fields	$\leftrightarrow$	Small x distributions in nuclei
Real-time dynamics	$\leftrightarrow$	EM probes, jets, heavy quarks
Gauge fields with boundary conditions/ event horizons	$\leftrightarrow$	Bulk behavior, soft photons and dileptons
Low-energy effective Theory of Everything: hydrodynamics	$\leftrightarrow$	Transport properties: shear and bulk viscosities, vorticity
Topology of gauge fields	$\leftrightarrow$	Local parity violation, spin

Asymptotic freedom and strong color fields

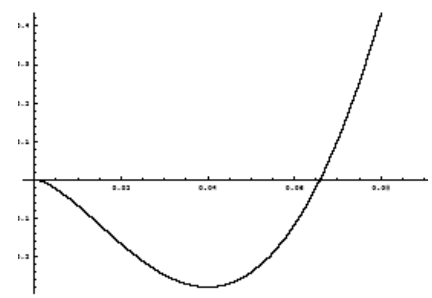


The effective potential: sum over 2D Landau levels

$$V_{\rm pert}(H) \; = \; \frac{g\,H}{4\,\pi^2} \int dp_z \sum_{n=0}^{\infty} \sum_{s_z=\pm 1} \sqrt{2\,g\,H\,(n+1/2-s_z)+p_z^2}.$$

Paramagnetic response of the vacuum:

$$\mathrm{Re}\,V_{\rm pert}(H) \; = \; \frac{1}{2}\,H^2 \; + \; (g\,H)^2\,\frac{b}{32\,\pi^2}\,\left(\ln\frac{g\,H}{\mu^2} \; - \; \frac{1}{2}\right)$$



1. The lowest level n=0 of radius $\sim (gH)^{-1/2}$ is unstable!

2. Strong fields ⟷ Short distances

Instability of perturbative QCD vacuum; What is the true ground state?

QCD and the classical gauge fields

Classical dynamics applies when the action $S = \int d^4x \;\; \mathcal{L}(x)$ is large in units of the Planck constant (Bohr-Sommerfeld quantization)

$$\frac{S_{QCD}}{\hbar} \sim \frac{1}{g^2\hbar} \int d^4x \text{ tr } G^{\mu\nu}(x)G_{\mu\nu}(x) \gg 1$$

(equivalent to setting $\hbar \to 0$)

=> Need weak coupling and strong fields

$$A^2 \ll \frac{p^2}{g^2}$$

weak field

$$D_\mu = \partial_\mu - igA_\mu^a t^a$$

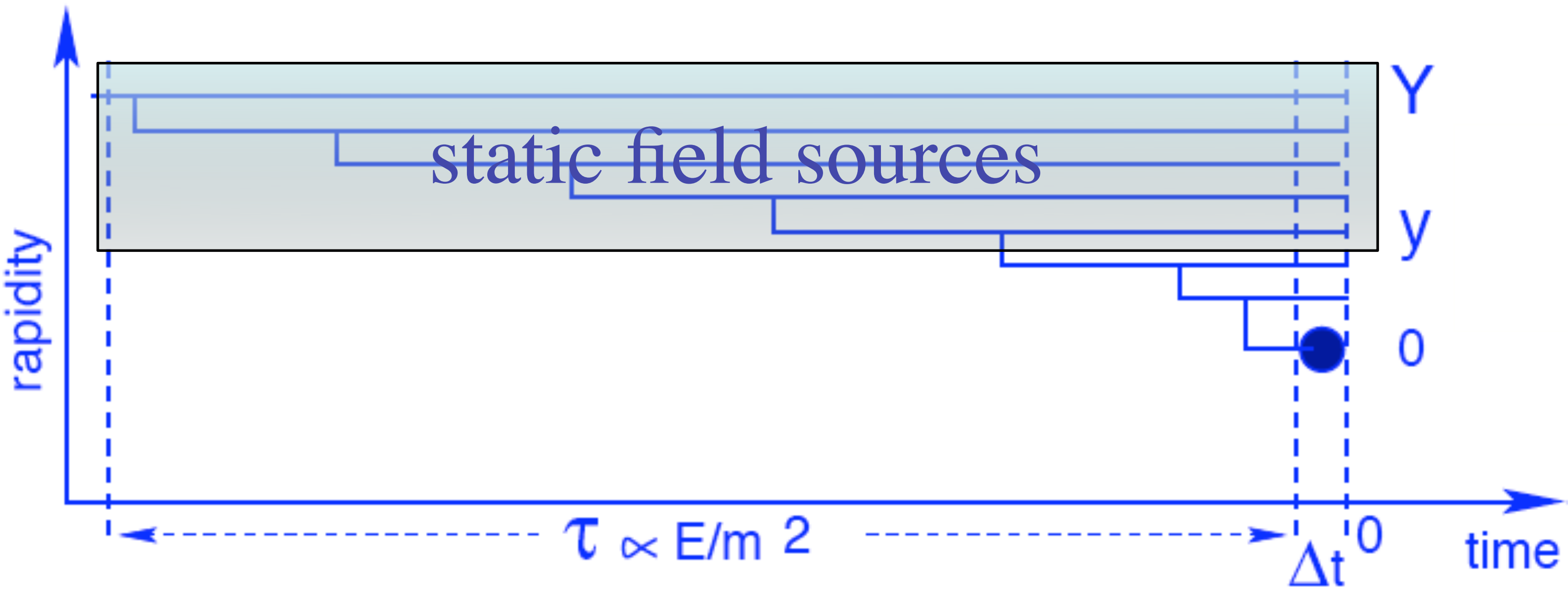
strong field

$$A^2 \sim \frac{p^2}{g^2}$$

$\boxed{\text{Weak coupling} \neq \text{perturbation theory!}}$

The origin of classical background field

Measurements:
suppression of hard processes at forward y;
depletion of back-to-back (quantum) correlations



Gluons with large rapidity and large occupation number act as a background field for the production of slower gluons

"Color Glass Condensate"

Measuring the strength of evolving color fields

PHENIX Coll., arXiv:1005.1627

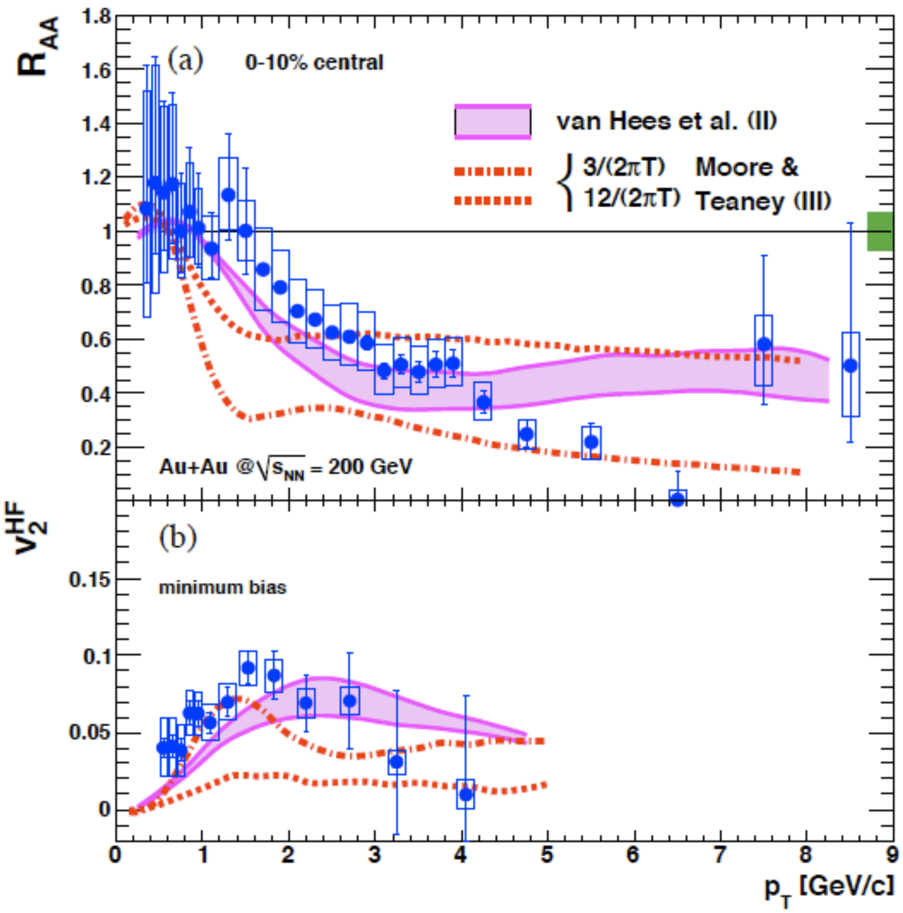


FIG. 40: (Color online) Comparison of Langevin-based models from [74–76] to the heavy flavor electron R_{AuAu} for 0–10% centrality and v_2 for minimum-bias collisions.

About the same behavior of heavy and light quarks - the color field is very strong,

$F \sim m_c^2$

may be weakly coupled but not perturbative

Measuring the strength of color fields

PHENIX Coll., arXiv:1005.1627

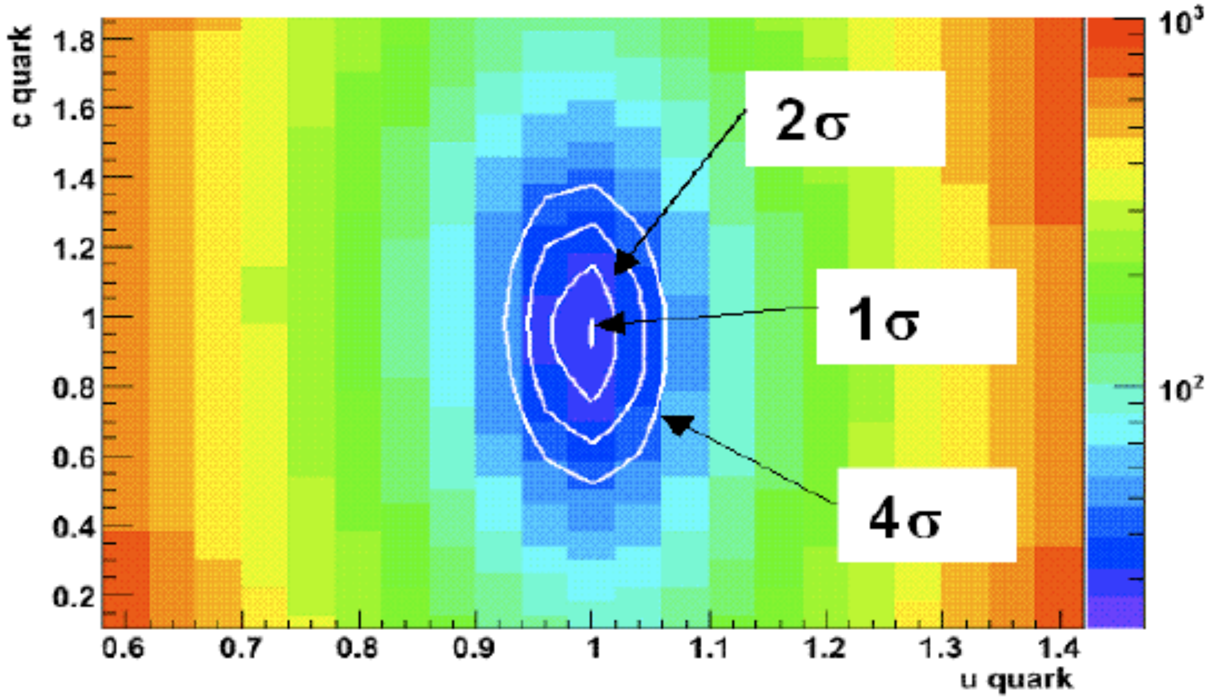


FIG. 46: (Color online) χ^2 map as a function of the light quark v_2 (horizontal axis) and charm quark v_2 (vertical axis), each divided by the measured light quark v_2.

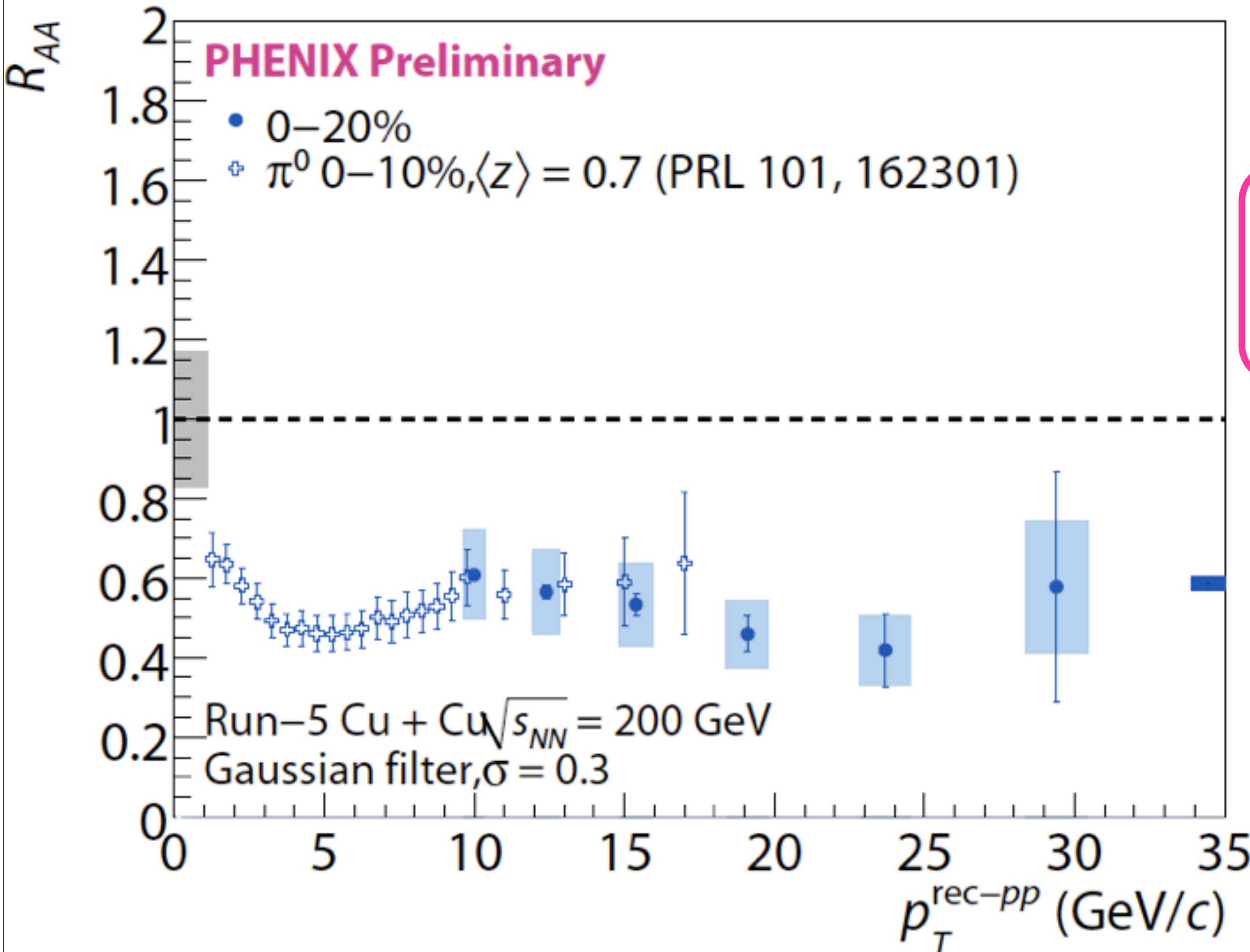
About the same behavior of heavy and light quarks - the color field is very strong,

$F \sim m_c^2$

may be weakly coupled but not perturbative

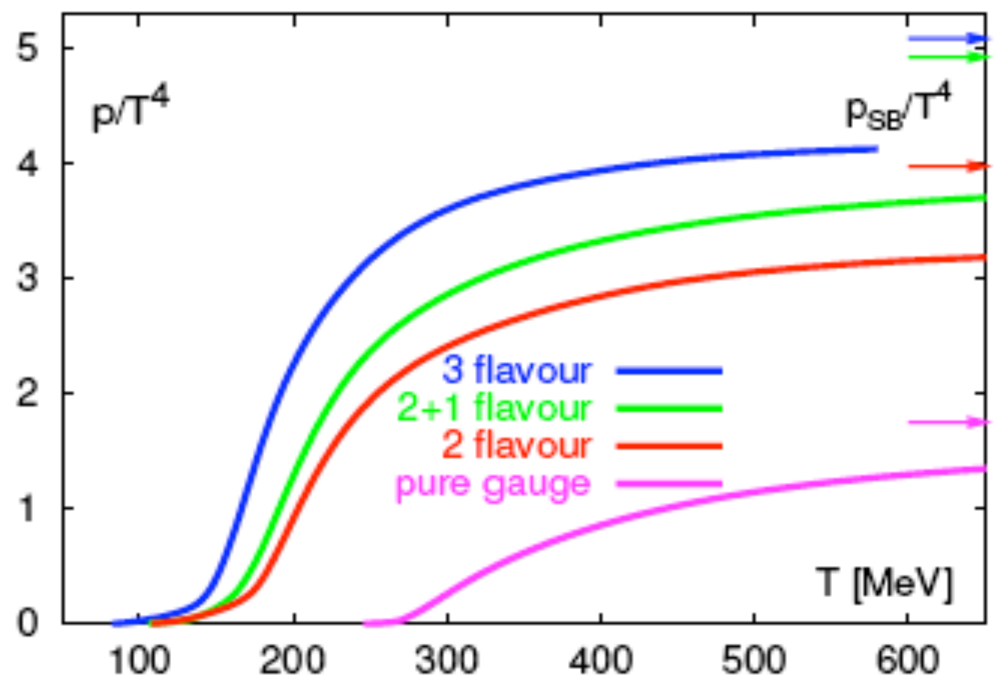
To calibrate the field strength, must separate b from c

Jets and leading hadrons: measuring the strength of color fields



Measurement: modification of jet shape?

QCD at high temperatures: gauge fields with boundary conditions



Phase transitions:

deconfinement

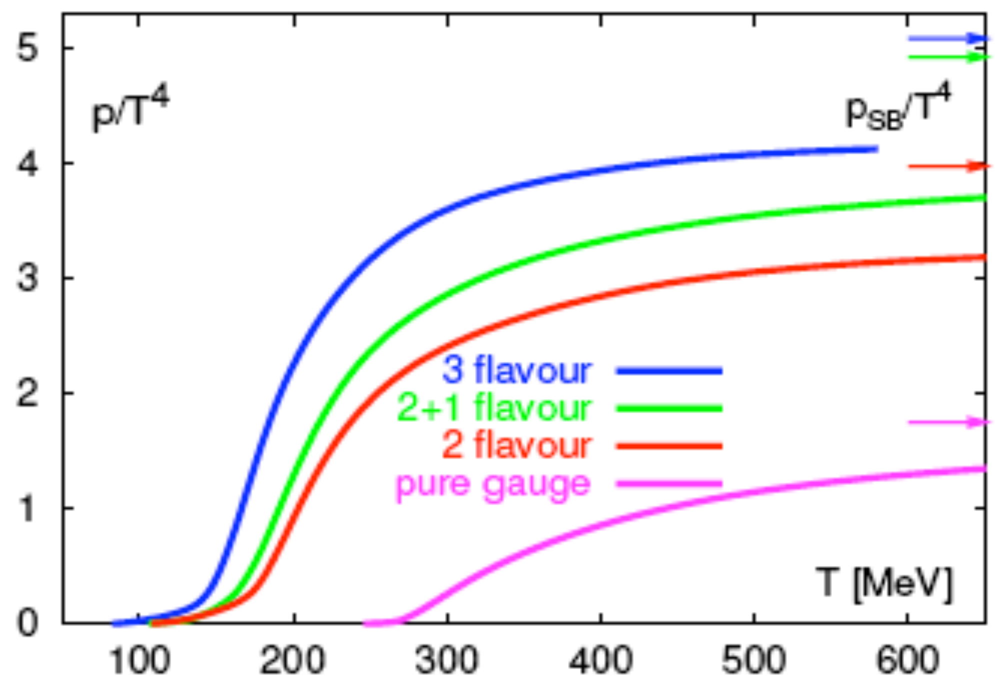
Chiral symmetry restoration

$U_A(1)$ restoration

Data from lattice QCD simulations F. Karsch et al

Is T~200 MeV "hot" or "cold"? The answer depends on the strength of interactions and gauge field dynamics

QCD at high temperatures: gauge fields with boundary conditions



Phase transitions:

deconfinement

Chiral symmetry restoration

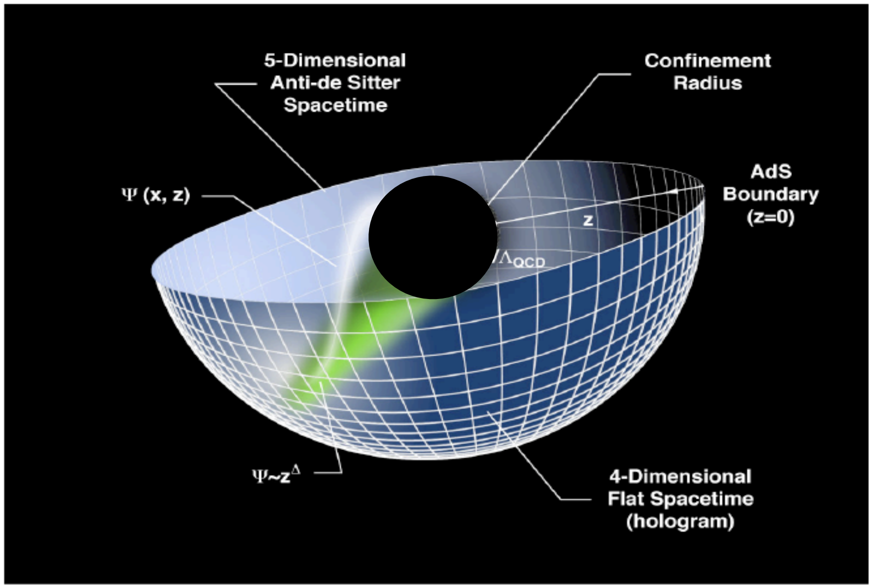
$U_A(1)$ restoration

Data from lattice QCD simulations F. Karsch et al

By convention hot, by convention cold, but in reality atoms and void;
and also in reality we know nothing, since the truth is at bottom.

Democritus

Low-energy effective ToE: hydrodynamics



Holographic view:

Particle contents of supergravity: **gravitons, dilatons, axions**

Caveman's view:

- Shear viscosity
- Bulk viscosity
- Rate of topological transitions

AdS$_5$ "Reality":

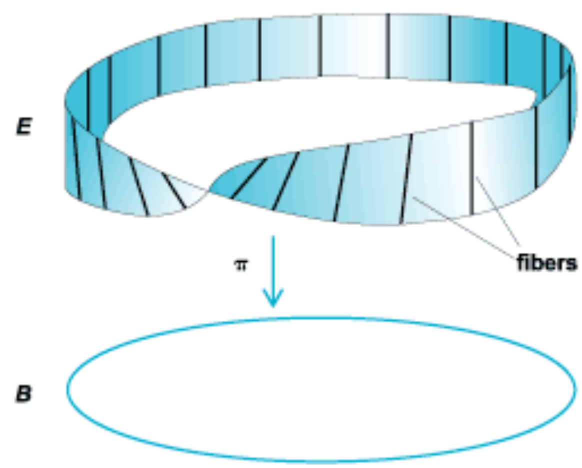
- Graviton propagation
- Dilaton propagation
- Axion propagation

Topology of gauge fields

Geometry ⟷ Physics

Riemannian connection ⟷ Gauge field

Curvature tensor ⟷ Field strength tensor



Möbius strip, the simplest nontrivial example of a fiber bundle

Gauge theories "live" in a fiber bundle space that possesses non-trivial topology (knots, links, twists,...)

Topology of gauge fields: Chern-Simons forms

CHARACTERISTIC FORMS

$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12} \wedge \theta_{13} \wedge \theta_{23} + \theta_{12} \wedge \Omega_{12} + \theta_{13} \wedge \Omega_{13} + \theta_{23} \wedge \Omega_{23}\}\,. \tag{6.1}$$

What does it mean for a gauge theory?

Geometry	⟷	Physics
Riemannian connection	⟷	Gauge field
Curvature tensor	⟷	Field strength tensor

$$\boxed{S_{CS} = \frac{k}{8\pi}\int_M d^3x\ \epsilon^{ijk}\left(A_i F_{jk} + \frac{2}{3}A_i[A_j, A_k]\right)}$$

breaks Parity invariance

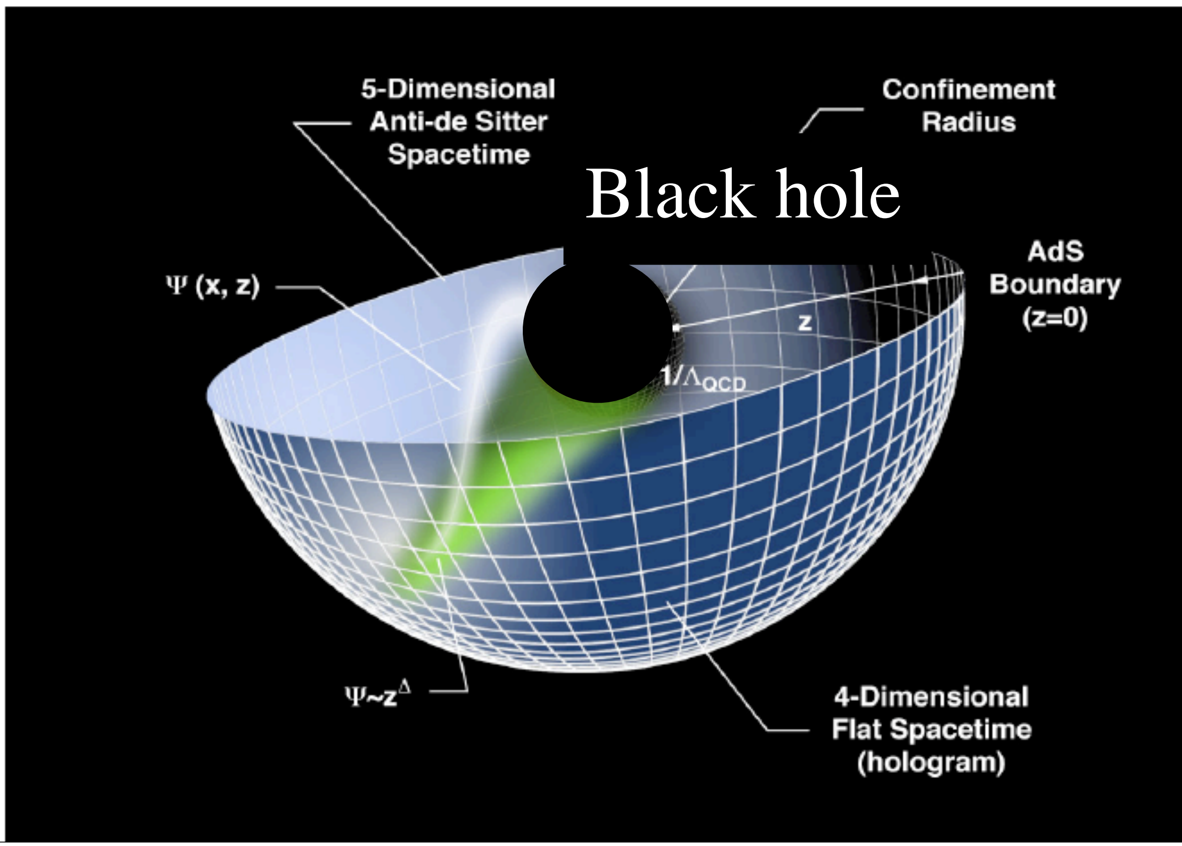
Abelian (**magnetic helicity**) non-Abelian

Topology at strong coupling: holographic view

Chern-Simons number diffusion rate at strong coupling

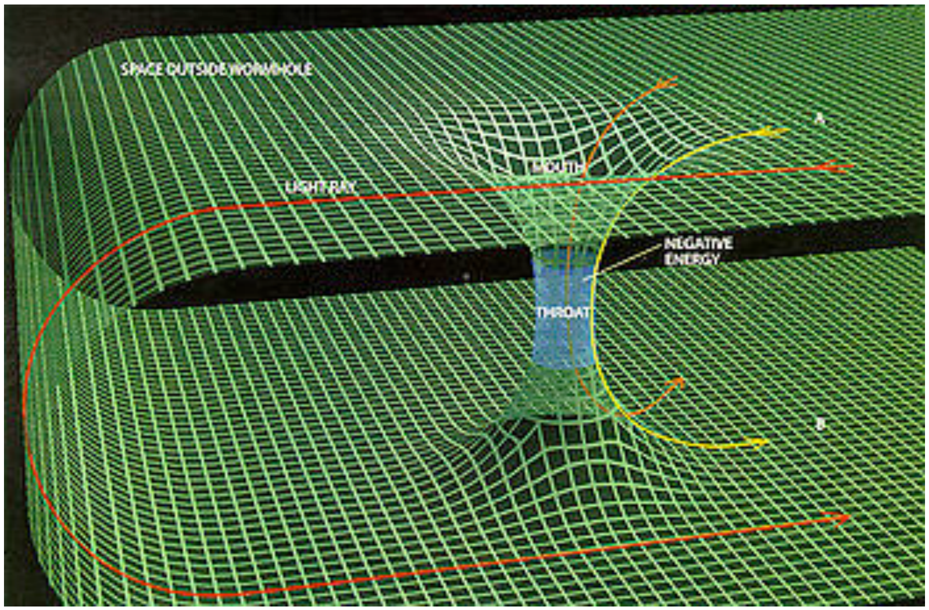
$$\Gamma = \frac{(g_{\rm YM}^2 N)^2}{256\pi^3} T^4$$

D.Son, A.Starinets hep-th/ 020505



NB: This calculation is completely analogous to the calculation of shear viscosity: **"perfect liquid" contains strong topological fluctuations**

Topology at strong coupling: holographic view



D-instanton as an Einstein-Rosen wormhole; the flow of RR charge down the throat of the wormhole describes change of chirality

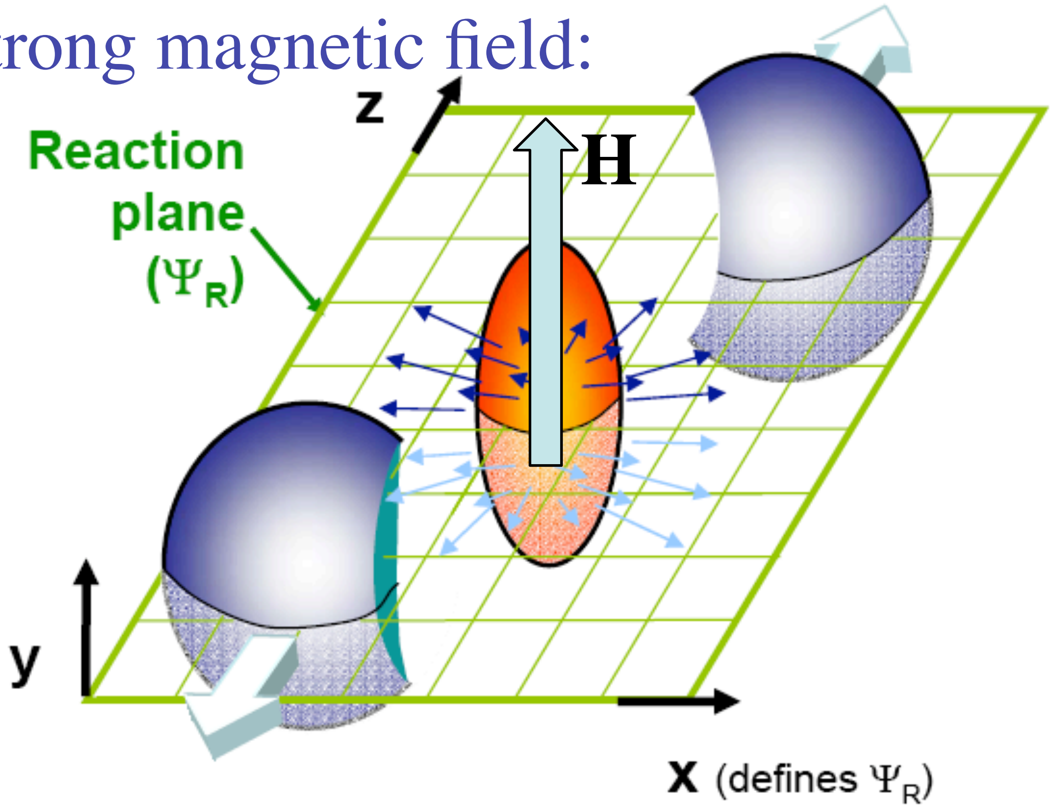
G. W. Gibbons, M. B. Green and M. J. Perry, Phys. Lett. B **370**, 37 (1996) [arXiv:hep-th/9511080].

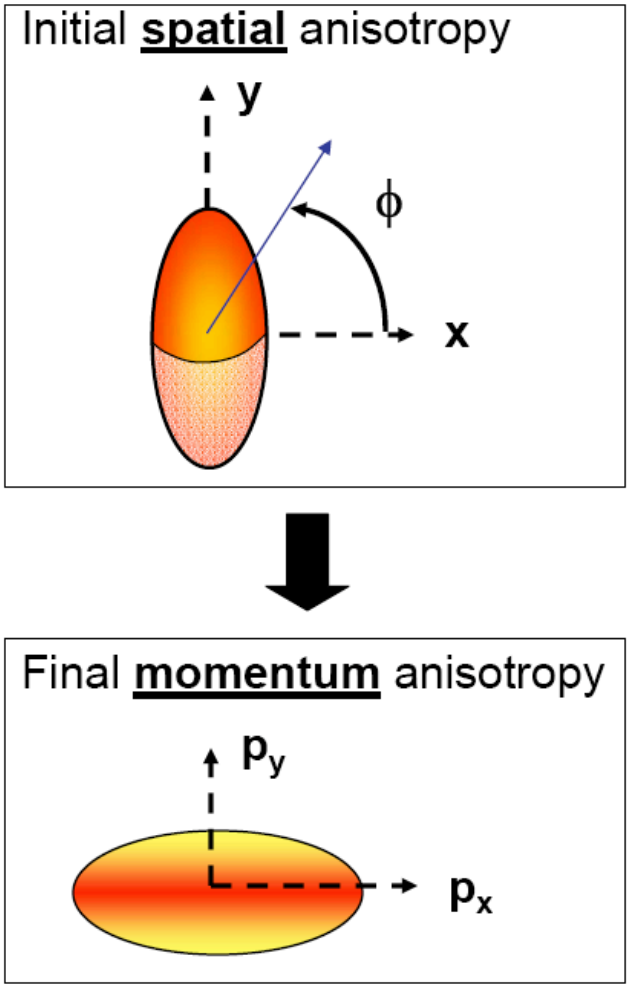
D-instantons as a source of multiparticle production in N=4 SYM?

DK, E.Levin, arXiv:0910.3355

Is there a way to observe topological charge fluctuations in experiment?

Relativistic ions create a strong magnetic field:





Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory

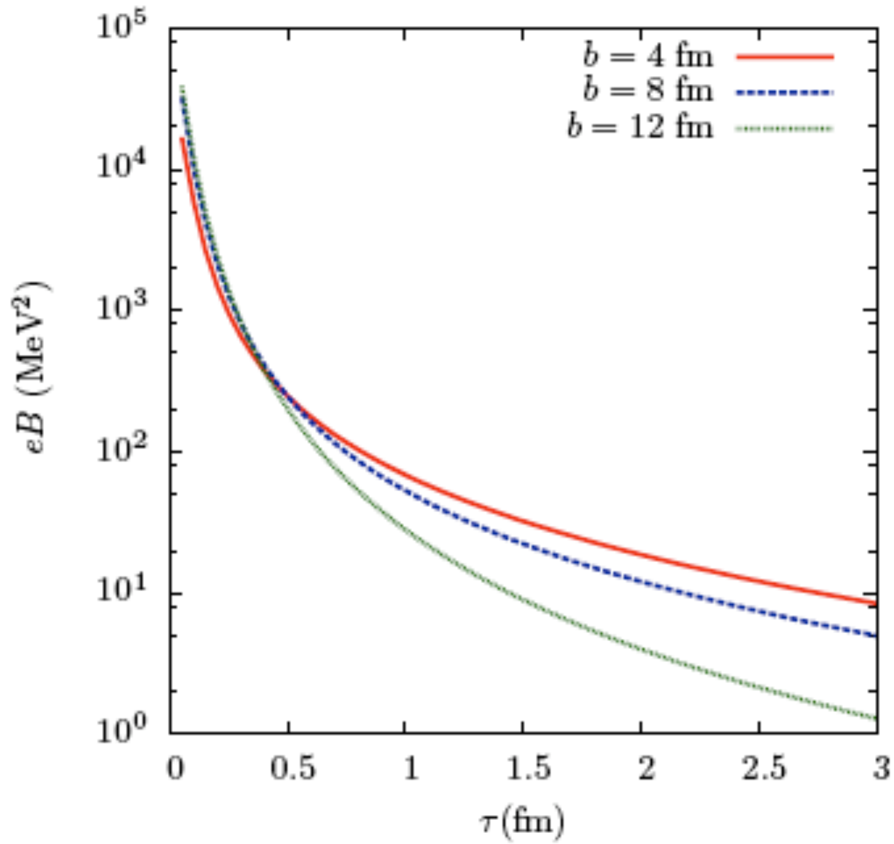


Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

In a conducting plasma, Faraday induction can make the field long-lived:
K.Tuchin, arXiv:1006.3051

Vorticity! Develop MHD of QCD fluid

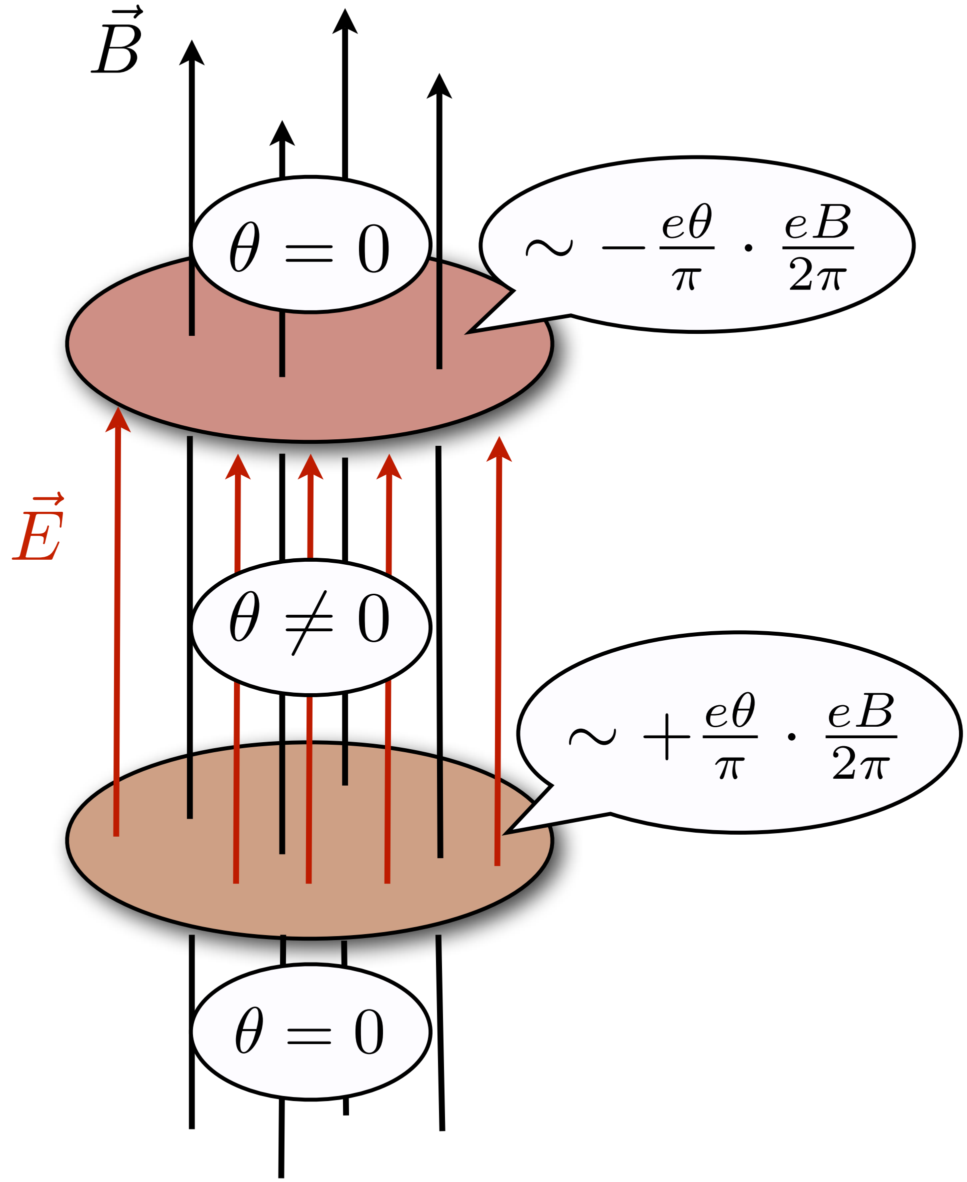
DK, McLerran, Warringa, Nucl Phys A803(2008)227

The Chiral Magnetic Effect

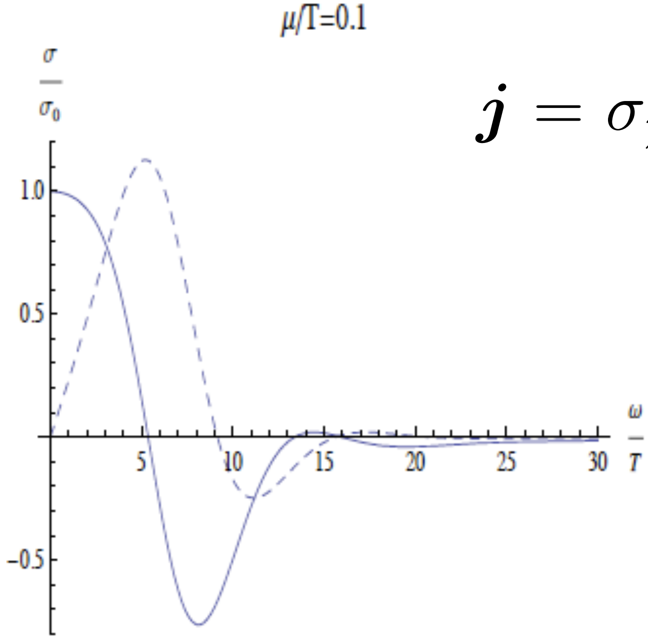
$$\vec{\nabla} \cdot \vec{E} = \rho + c\vec{P} \cdot \vec{B}$$

$$\vec{P} \equiv \vec{\nabla}\theta$$

$$\boxed{d_e = \sum_f q_f^2 \left(e\,\frac{\theta}{\pi}\right) \left(\frac{eB \cdot S}{2\pi}\right) L}$$



Holographic CME: is the current renormalized at strong coupling?



$$\boldsymbol{j} = \sigma_\chi \boldsymbol{B}$$

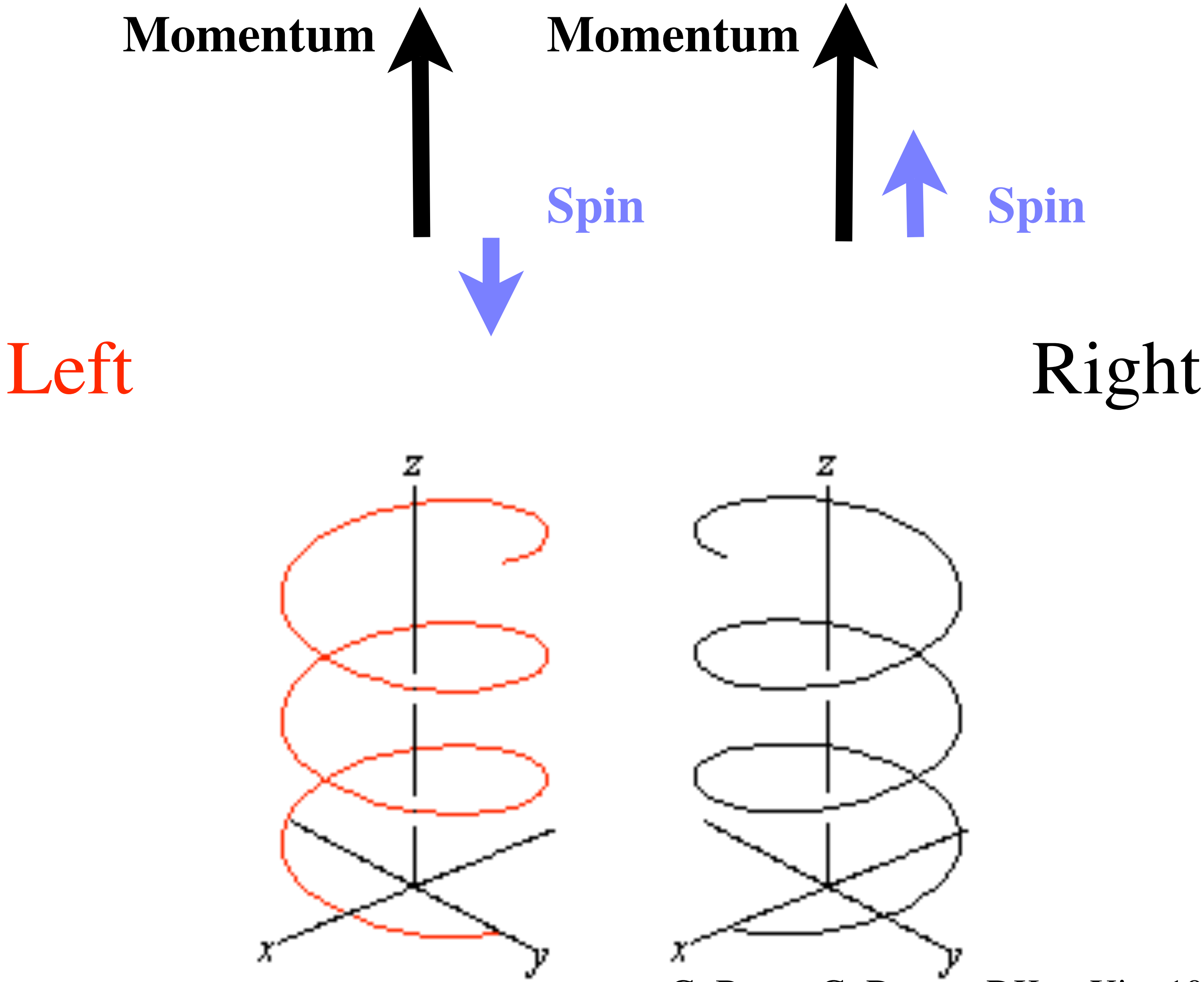
H.-U. Yee, arXiv:0908.4189, JHEP 0911:085, 2009

Recent progress:
V.Rubakov, arXiv:1005.1888;
A. Gynther, K. Landsteiner, F. Pena-Benitez, A. Rebhan, arXiv:1005.2587

CME current is the same at strong and weak coupling

What carries the current at strong coupling?

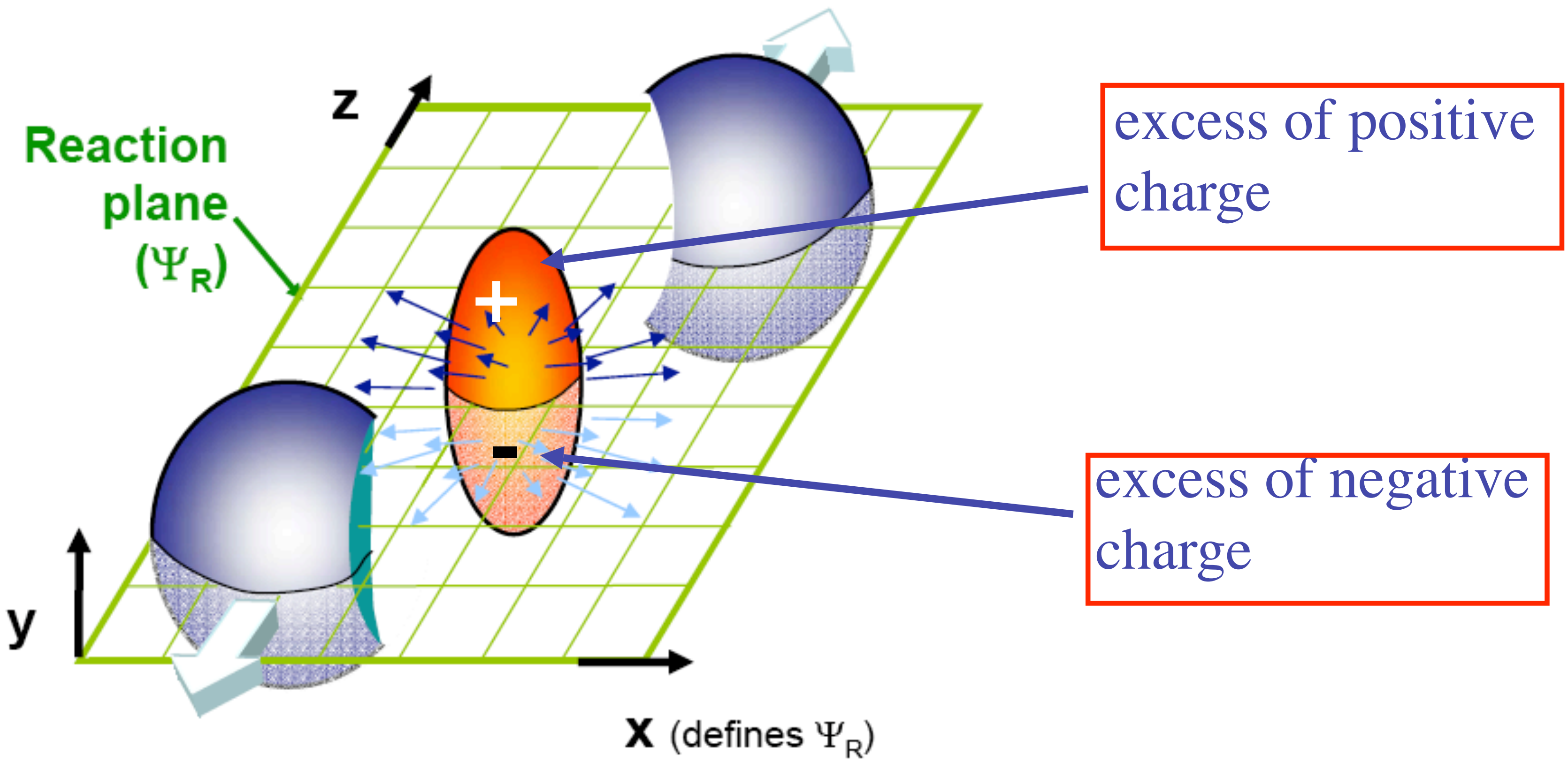
CME in the chirally broken phase



G. Basar, G. Dunne, DK, arXiv: 1003.3464; PRL

“Quark-gluon solenoid”, **Physics**, June 18, 2010

Charge asymmetry w.r.t. reaction plane as a signature of local strong P violation

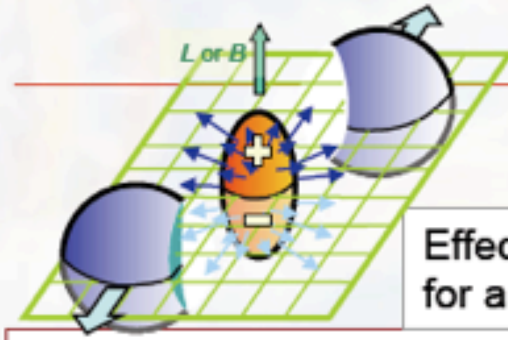


Electric dipole moment of QCD matter!

DK, Phys.Lett.B633(2006)260 [hep-ph/0406125]

Observable

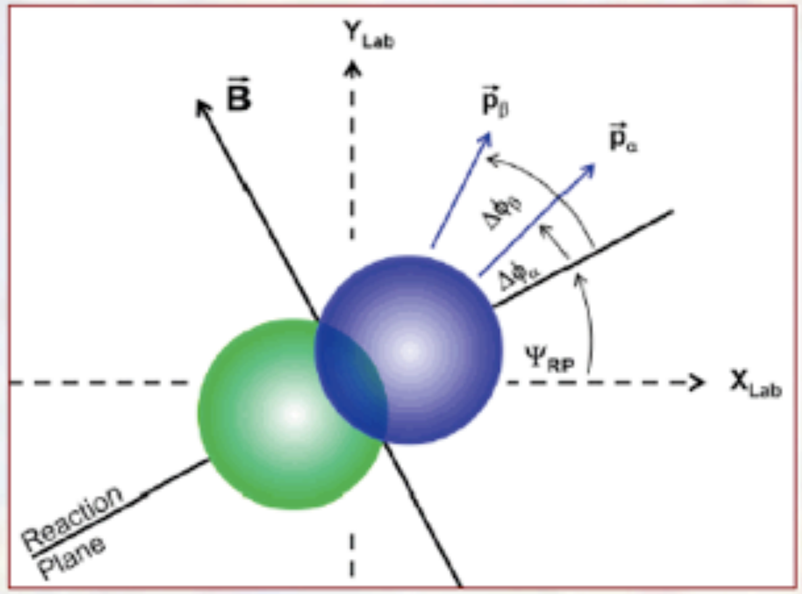
S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Effective particle distribution for a certain Q.

$$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2\,v_{2,\alpha}\cos(2\Delta\phi) + \ldots$$
$$+ \; 2a_{1,\alpha}\sin(\Delta\phi) + 2\,a_{2,\alpha}\sin(2\Delta\phi) + \ldots,$$

$$\Delta\phi = (\phi - \Psi_{RP})$$



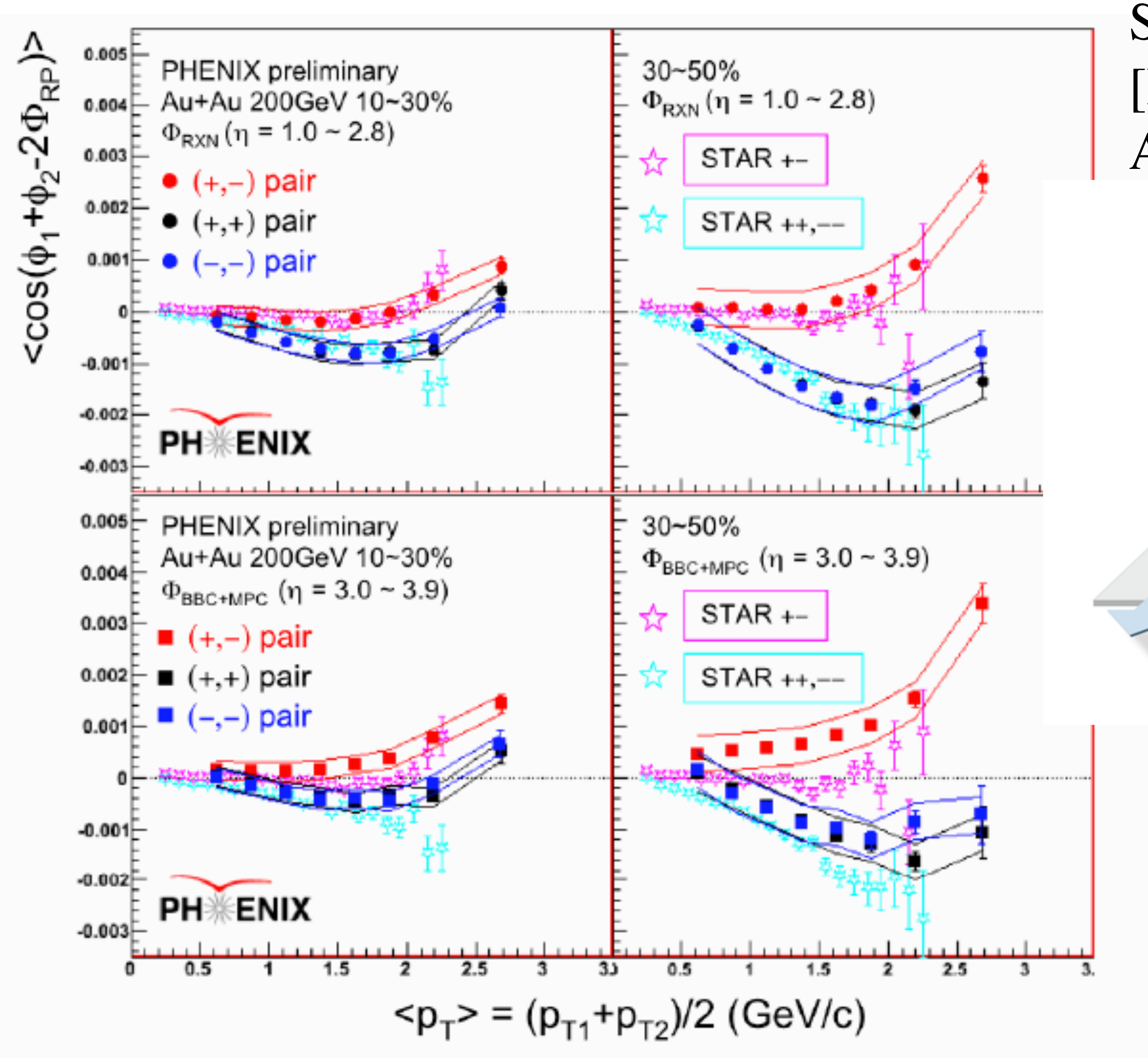
- The effect is too small to observe in a single event
- The sign of Q varies and $\langle a \rangle = 0$ (we consider only the leading, first harmonic) ➔ one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, $\mathcal{P}$-even quantity (!)
- $\langle a_\alpha a_\beta \rangle$ is expected to be ~ 10^{-4}
- $\langle a_\alpha a_\beta \rangle$ can not be measured as $\langle \sin\varphi_\alpha \sin\varphi_\beta \rangle$ due to large contribution from effects not related to the orientation of the reaction plane

➔ study the difference in corr's in- and out-of-plane

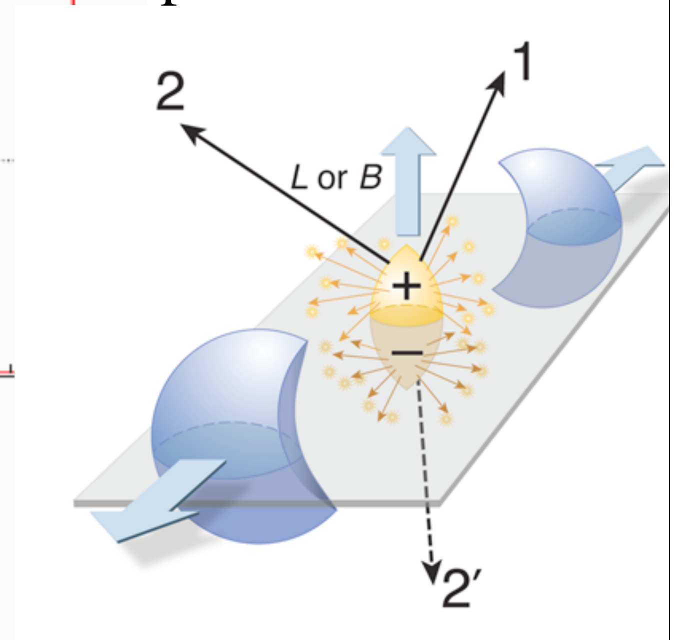
$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle =$$
$$= \langle\cos\Delta\phi_\alpha\,\cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha\,\sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B^{in}] - [\boxed{\langle a_\alpha a_\beta\rangle} + B^{out}].$$

$$B^{in} \approx B^{out}, \quad v_1 = 0$$

A practical approach: three particle correlations: $\langle\cos(\phi_a + \phi_\beta - 2\phi_c)\rangle = \langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle\, v_{2,c}$



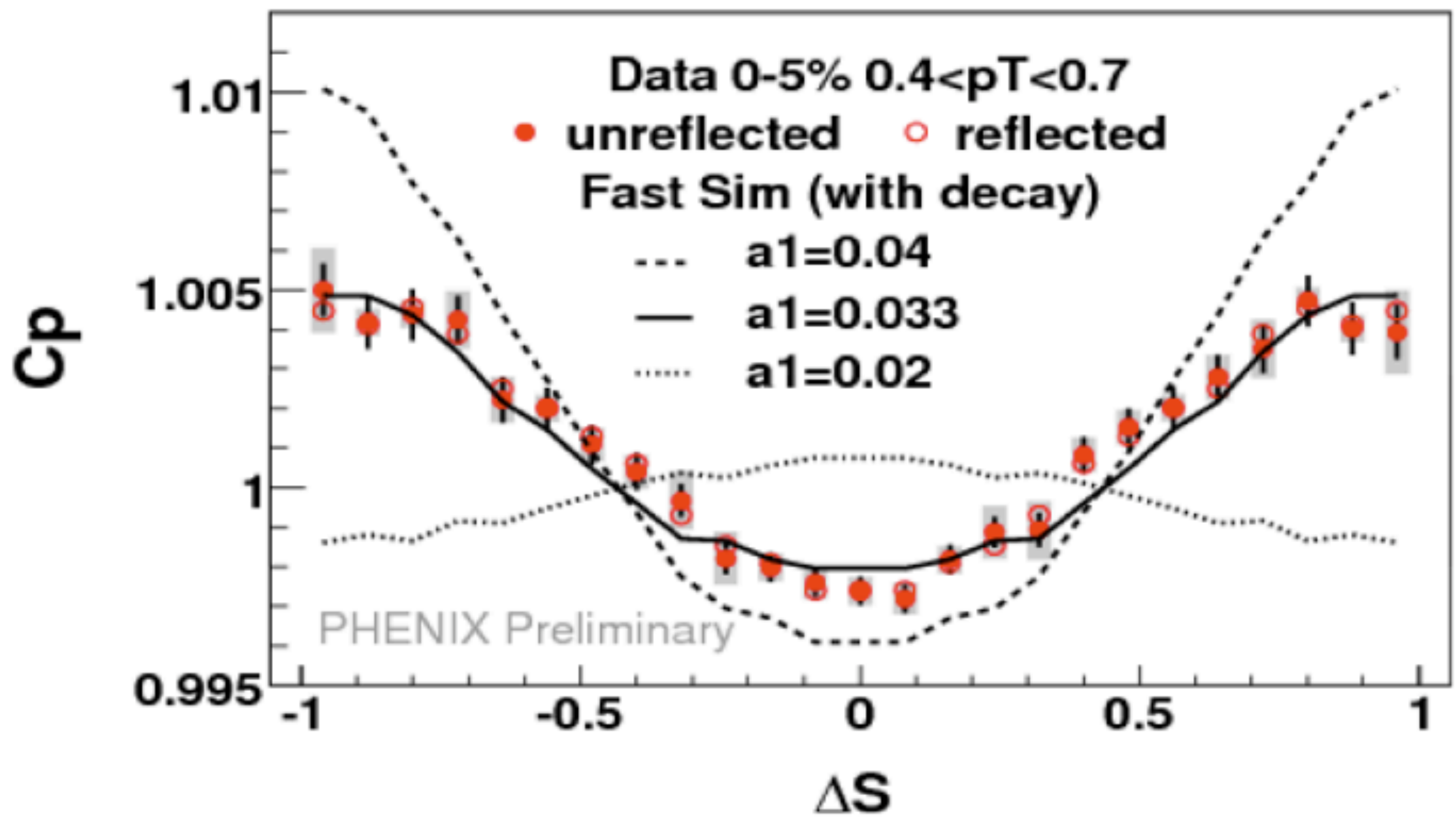
S.Esumi et al
[PHENIX Coll]
April 2010



R. Lacey
[PHENIX Coll]
Talk at "CP-odd",
April 26-30, 2010

Relatively good agreement between PHENIX & STAR

Multi-particle correlation Results



Concave shape validates charge asymmetry w.r.t the reaction plane

N. Ajitanand [PHENIX Coll], Talk @ BNL, Dec 2009

Are the observed fluctuations of charge asymmetries a convincing evidence for the local parity violation?

A number of open questions that still have to be clarified:

in-plane vs out-of-plane,
new observables?

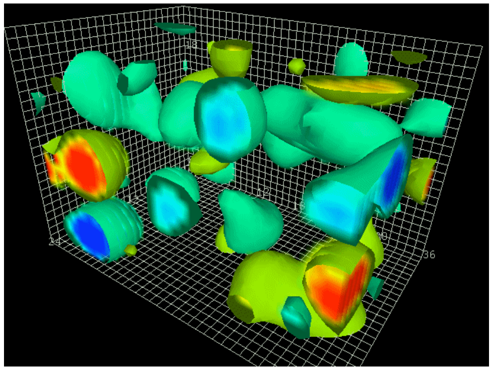
A. Bzdak, V. Koch, J. Liao,
arXiv:0912.5050; 1005.5380

physics "backgrounds"

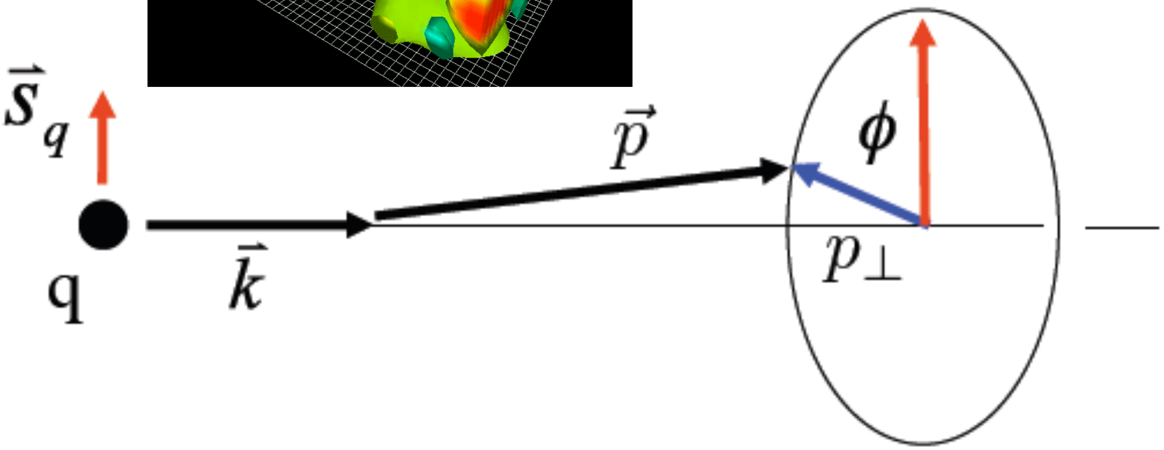
M. Asakawa, A. Majumder, B. Muller,
arXiv:1003.2436
S. Pratt and S. Schlichting, arXiv:1005.5341
F. Wang, arXiv: 0911.1482

Fortunately, a number of analytical and numerical (lattice) tools are available to theorists,
and the new data (low energy, **PID asymmetries**, U-U) will hopefully come - this question can be answered!

Topology of gauge fields, LPV, and the fragmentation of polarized quarks



Z. Kang, DK, arXiv:1006.2132



P-odd:

$$D_{\pi/q^\uparrow}(z,p_\perp) = D(z,p_\perp^2) + H_1^\perp(z,p_\perp^2)\frac{(\hat{k}\times p_\perp)\cdot s_q}{M} + \widetilde{H}_1^\perp(z,p_\perp^2)\frac{p_\perp\cdot s_q}{M}$$

Z. Kang, DK, arXiv:1006.2132

Cross section in e+e- annihilation:

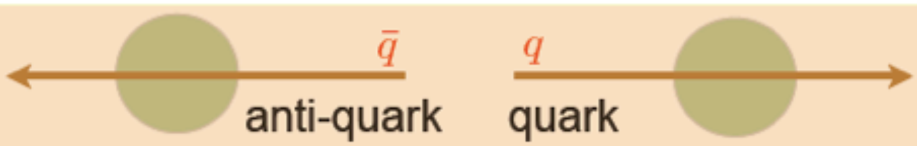
Data and tests (Belle, RHIC) forthcoming:
M.Grosse-Perdekamp, A. Vossen,
A. Deshpande, ...

$$
\begin{aligned}
\frac{d\sigma}{dz_1 dz_2 d\cos\theta d(\phi_1+\phi_2)} &= \sigma_0 \sum_q e_q^2 \Big\{ (1+\cos^2\theta)\left[D_q(z_1)D_{\bar q}(z_2) - \widetilde{D}_q(z_1)\widetilde{D}_{\bar q}(z_2)\right] \\
&+ \sin^2\theta\cos(\phi_1+\phi_2)\left[H_q^\perp(z_1)H_{\bar q}^\perp(z_2) + \widetilde{H}_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2)\right] \\
&+ \sin^2\theta\sin(\phi_1+\phi_2)\left[H_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2) - \widetilde{H}_q^\perp(z_1)H_{\bar q}^\perp(z_2)\right]\Big\}
\end{aligned}
$$

"Collins effect"

P-odd, only EbyE

- Physical pictures:
  - P-odd times P-odd terms:



$\widetilde{D}_q(z_1)\widetilde{D}_{\bar q}(z_2)$ OR $\widetilde{H}_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2)$

  - P-odd term alone:

$H_q^\perp(z_1)\widetilde{H}_{\bar q}^\perp(z_2)$

$-\widetilde{H}_q^\perp(z_1)H_{\bar q}^\perp(z_2)$

Summary

The next decade presents us with
a unique chance to pursue the centuries-old
quest for understanding the structure of matter

- ☑ "Atoms" identified: quarks and leptons
- ☐ Geometry (gauge field dynamics)
- ☐ Void (the structure of the vacuum)

The next step:
from particles ("atoms") to fields (geometry)

QCD: understanding the dynamics of gauge fields (geometry)

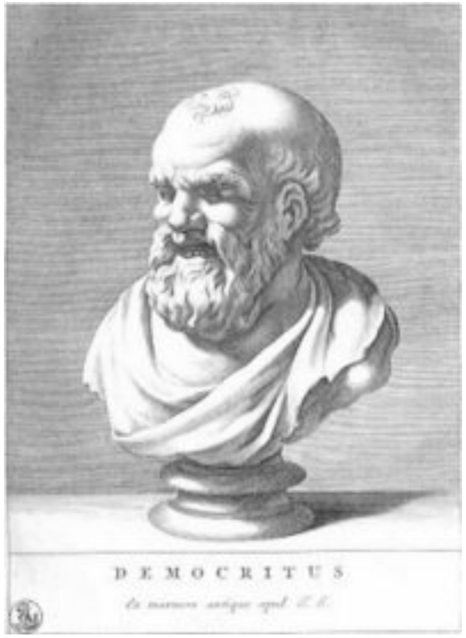
Problem		Measurements at RHIC
❑ Weak/vacuum fields	⟷	❑ Spin, parton fragmentation
❑ Strong static fields	⟷	❑ Small x distributions in nuclei
❑ Real-time dynamics	⟷	❑ EM probes, jets, heavy quarks
❑ Gauge fields with boundary conditions/ event horizons	⟷	❑ Bulk behavior, soft photons and dileptons
❑ Low-energy effective Theory of Everything: hydrodynamics	⟷	❑ Transport properties: shear and bulk viscosities, vorticity
❑ Topology of gauge fields	⟷	❑ Local parity violation, spin

Extra slides

Atomism vs corpuscularianism:

are quarks and leptons the ultimate indivisible "atoms"of Nature?

Leucippus, V B.C.



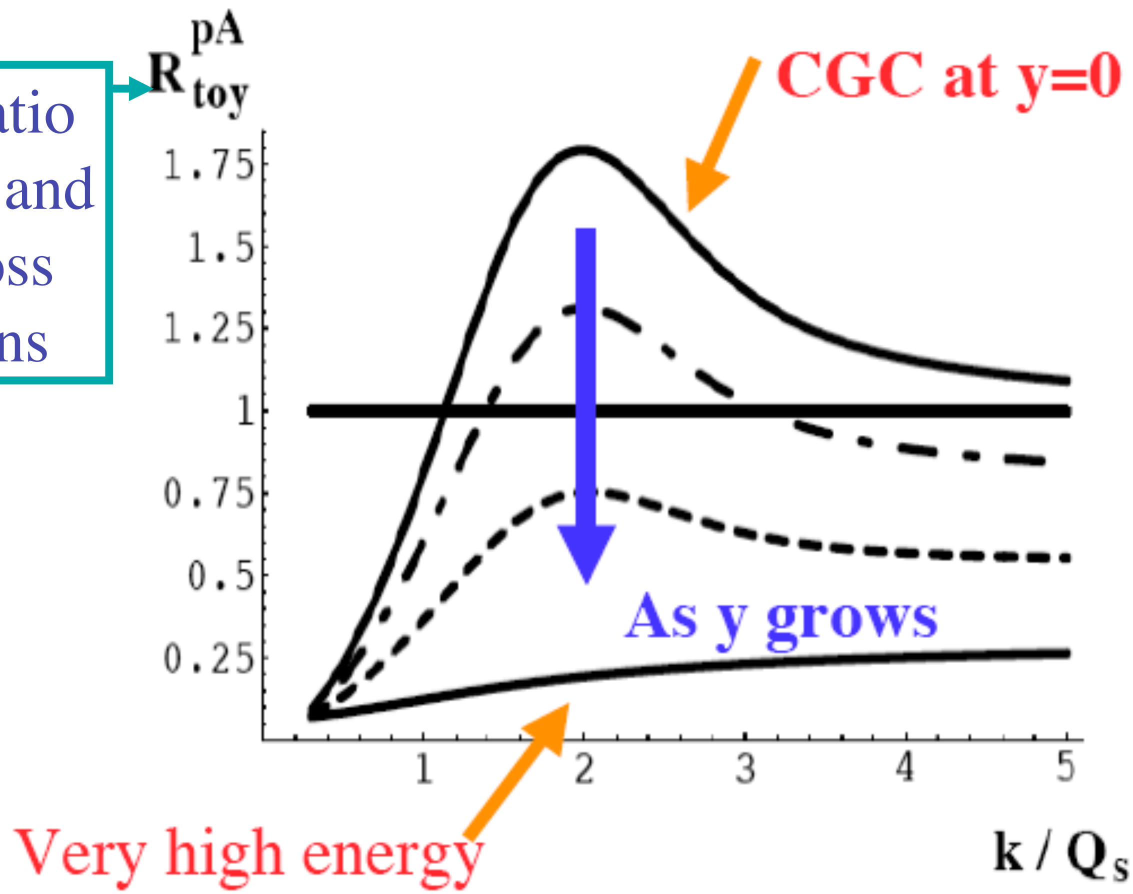
Democritus, ca 460 -370 B.C.

Robert Boyle (1627–1691)

Page from alchemic treatise of [Ramon Llull](), 16th century

Static strong color fields: nuclear gluon distributions at small x

The ratio of pA and pp cross sections



transverse momentum

At large rapidity y (small angle) expect suppression of hard particles!

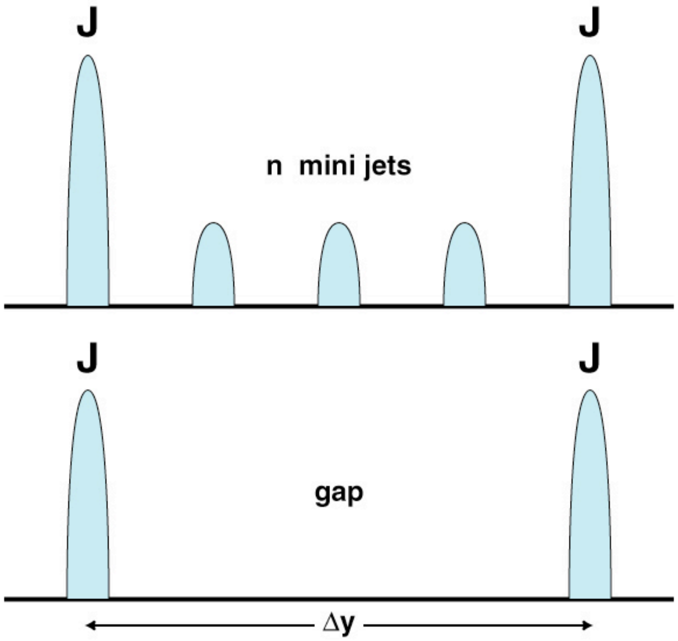
DK, Levin, McLerran; Albacete,Armesto,Kovner, Wiedemann; DK,Kovchegov, Tuchin

Are the effects observed at forward rapidity due to parton saturation in the CGC?

•Back-to-back correlations for jets separated by several units of rapidity are very sensitive to the evolution effects

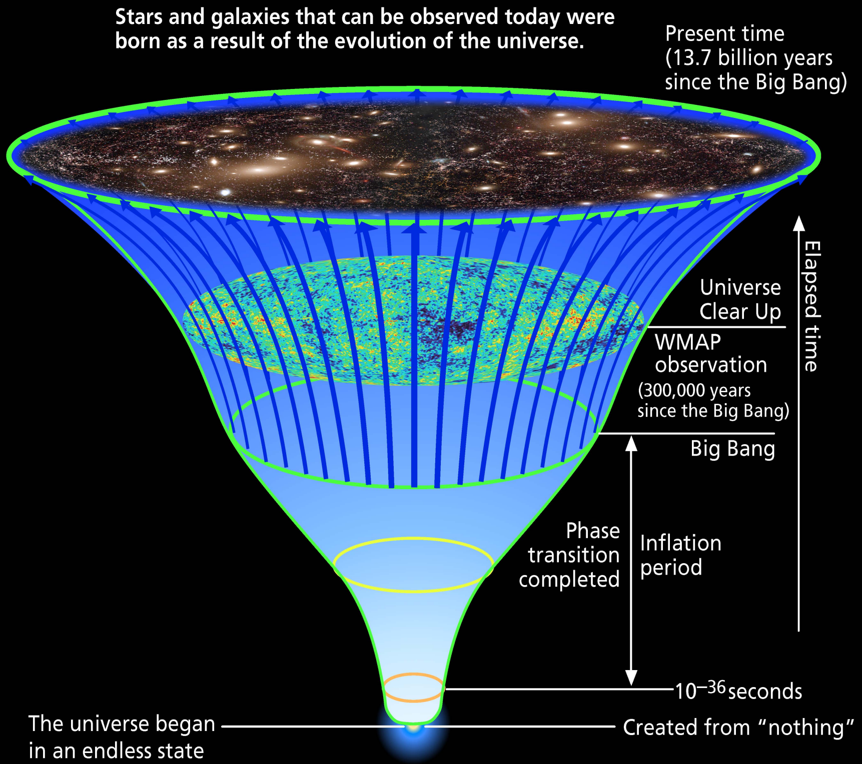
("Mueller-Navelet jets")

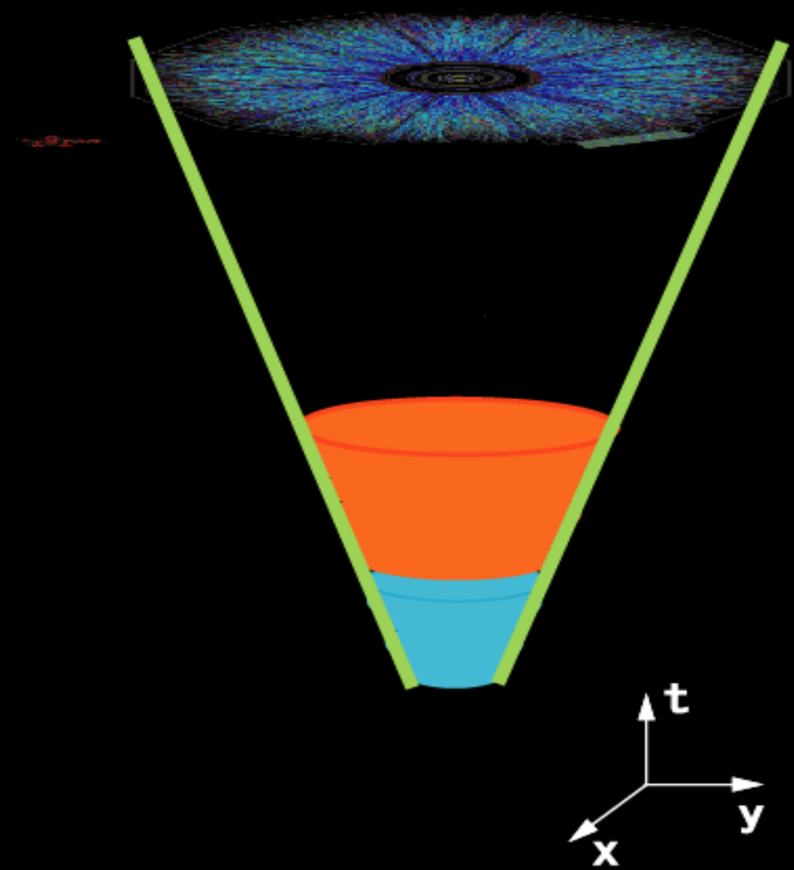
and to the presence of CGC



Forward measurements at RHIC:
Do back-to-back correlations really disappear?

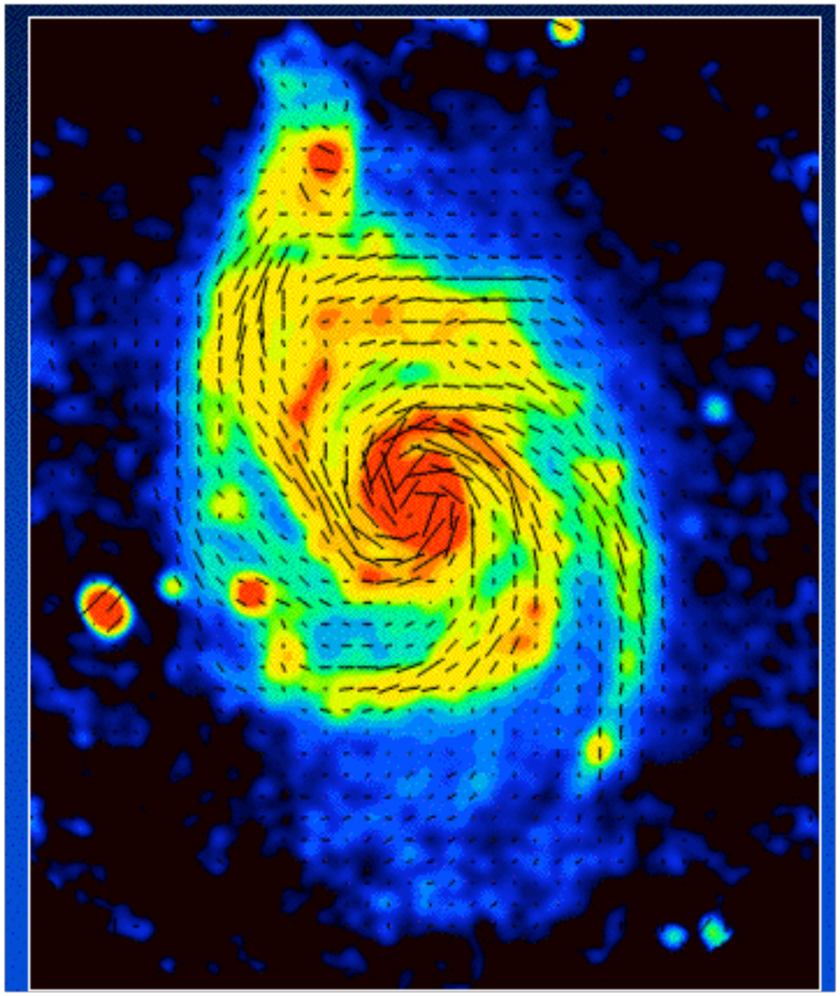
Topology in the Early Universe?





T.Hatsuda

What is the origin of cosmic magnetic helicity?



Magnetic fields are abundant in the Universe at large scales:

3 μG field in Milky Way;

1-40 μG fields in clusters of galaxies

Is the entire Universe chiral?

e.g. M.Longo, arXiv:0812.3437;

thanks to J.Bjorken

Magnetic field in M51:
Polarization of emission
Beck 2000

Chiral magnetic spiral in the Early Universe?

Affleck-Dine baryogenesis